CIRCULAR NO. 61 JANUARY, 1929
UNITED STATES DEPARTMENT OF AGRICULTURE
WASHINGTON, D. C.

# A HIGH-PRESSURE GAS-COMPRESSION SYSTEM

By J. R. Dilley, *Associate Mechanical Engineer*, and W. L. Edwards, *Associate Engineer, Fertilizer and Fixed Nitrogen Investigations, Bureau of Chemistry and Soils.*

CONTENTS



## INTRODUCTION

The comparatively rapid growth of the synthetic-ammonia industry in the last few years is largely responsible for the increasing use of gases and gaseous mixtures at high pressures. The magnitude of what are here called high pressures lies within the range of 300 to 1,500 atmospheres (4,500 to 22,500 pounds per square inch). New industrial processes which involve the use of such pressures are constantly being brought to the fore. The synthesis of methanol and the higher alcohols from carbon monoxide and hydrogen, the hydrogenation of naphthalene, and the synthesis of urea are examples of this development.

Nitrogen fixation and allied processes using gases at high pressures are not the only ones in which the application of high pressure and high temperature subject the apparatus to severe service conditions. Hydraulic pressing and the high-pressure cracking processes of the oil industry are other instances which show the need of more extensive knowledge of the materials and proper design to measure up to the requirements.

The success of these processes is in a great measure due to engineering design. Engineering practice is changing rapidly and developing to meet these new conditions. Until recent years, most of the high-pressure design has been concerned with hydraulic equipment, which in most cases does not involve pressures in excess of a few hundred atmospheres. The tendency to adopt hydraulic design for gas-pressure apparatus has generally proved unsatisfactory, however, and an entirely new basis of engineering design is required to meet the new conditions.

20398—29——1

Industrial applications of the direct synthetic-ammonia process require pressures ranging from 100 to 900 atmospheres. Knowledge of the properties of the gases at these pressures has naturally necessitated research work, which is being done in various laboratories at pressures up to 1,000 atmospheres, although some work has been done at 1,500 atmospheres.

The engineer is handicapped in the actual physical design, not only by the lack of definite facts and principles relating to high pressures but also by the lack of good engineering practice. The need of materials to withstand the combination of high pressure, high temperature, and corrosion presents another problem to the designer.

The knowledge that has been gained through several years' experience with high-pressure gas reactions has enabled the fixed nitrogen research laboratory to develop a system for experimental work with gases and gaseous mixtures at pressures up to 1,500 atmospheres. There have been presented in the technical press, from time to time, articles suggesting such experimental equipment. These articles have brought forth numerous inquiries from universities and industrial concerns regarding individual pieces of apparatus. There are, however, no detailed descriptions enabling anyone to construct such apparatus completely. It is for those who may be interested in making and assembling such apparatus for research that this circular is presented. The equipment herein described is in use at the fixed nitrogen research laboratory and can be fully recommended for research work with gases at normal temperatures and at pressures up to 1,500 atmospheres (22,500 pounds per square inch).

## DESCRIPTION AND OPERATION

Primarily the system consists of two cylinders in which the gas is compressed above a water column actuated by a hydraulic pump. The first cylinder is the compression cylinder, into which gas is alternately admitted from a low-pressure storage supply, compressed by action of the hydraulic pump, and then released into the second or storage cylinder. The repeated forcing of more gas into the second cylinder is continued until the desired pressure is obtained in this cylinder.

The complete compression system is shown in Figure 1, and the method of operation is as follows: Gas from a storage supply at a pressure of 100 to 300 atmospheres (1,500 to 4,500 pounds per square inch) is admitted to both the compression cylinder and the storage cylinder by opening valve *a*, valve *b* being open and valve *c* closed. Valves *a* and *b* are then closed, and by operating the hydraulic pump water is forced into the bottom of the compression cylinder, compressing the gas column above. When the pressure in the first cylinder is somewhat greater than that in the second, the pump is stopped, valve *b* is opened, and the pressure in the two cylinders is equalized. Valve *b* is then closed, and the water is drained out of the compression cylinder through the blow-off valve *d*. A fresh charge of gas is admitted into the first cylinder through valve *a* and is compressed to a greater pressure than that of the second cylinder by the action of the hydraulic pump. Valve *b* is opened, and the pressure in both cylinders is again equalized; the water is again

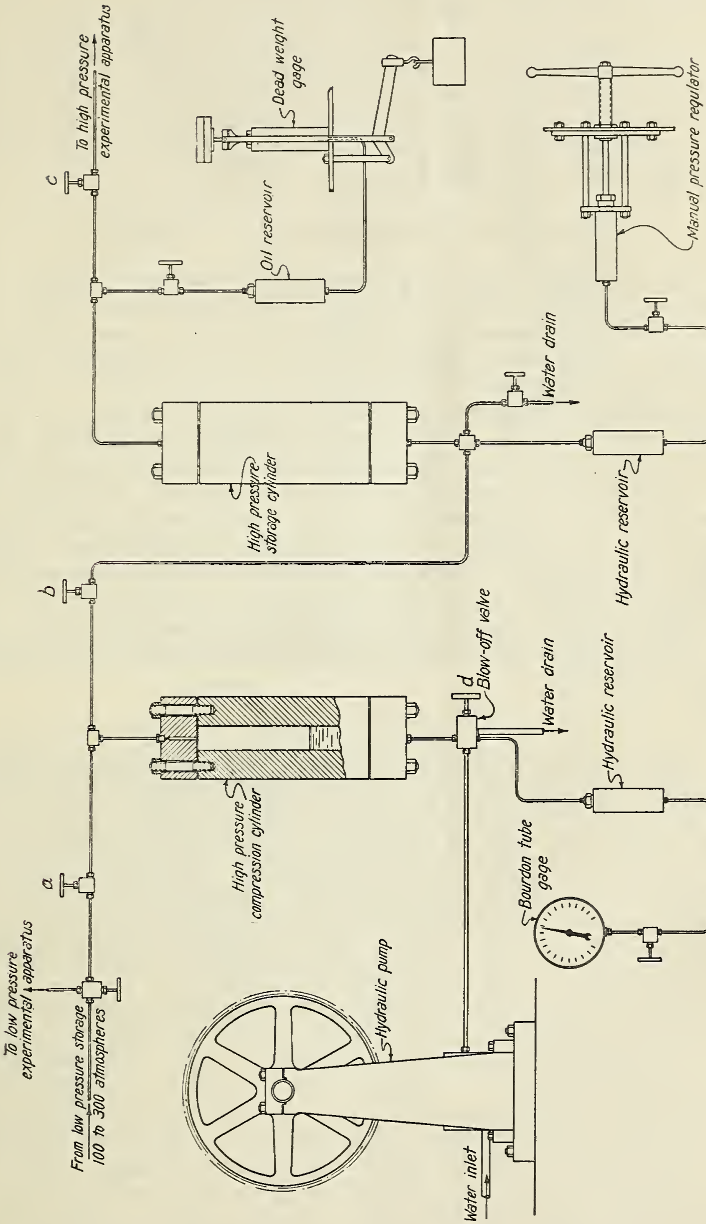



FIG. 1.—Flow chart of high-pressure gas-compression system

drained from the first cylinder after first closing valve *b*. This alternate filling and compressing is repeated until the desired gas pressure is obtained. The passage of the high-pressure gas to the experimental apparatus is controlled by the valve *c*. In order to obtain accurate pressure measurements a dead-weight gauge is connected to the exit line of the storage cylinder. Slight variations in pressure are obviated by a manual-pressure regulator, which is connected to the bottom of the storage cylinder. In the flow chart, Figure 1, a cross valve is shown in the line just ahead of the supply valve *a*. This valve can be connected through tubing to any experimental equipment for testing at the low pressure.

## LOW-PRESSURE COMPRESSOR AND STORAGE

At this laboratory gas is compressed to storage pressure, 200 atmospheres (3,000 pounds per square inch), by a four-stage compressor. This compressor has a delivery of 13 cubic feet of free gas per minute. Compressors such as this are readily available commercially. The storage system has a capacity of 24 cubic feet. Cylinders for low-pressure storage can also be purchased, or when the storage pressure is not too high the ordinary gas-shipping cylinder can be used. A relief valve should be installed on the low-pressure storage to take care of any excess pressure due to possible leakage of the inlet valve to the compression cylinder. Compressor and storage capacities can be arranged to suit individual requirements. Small laboratory compressors with a displacement of 5 cubic feet and compressing up to 4,000 pounds per square inch are available. If desired, compressed gas from shipping cylinders may be used. This preliminary compression is not actually necessary, but as a timesaver its value is obvious.

## HYDRAULIC PUMP

The fixed nitrogen research laboratory has two similar compression systems. The one system has a hydraulic pump which was designed and built at this laboratory. This pump is of the two-plunger type, with 3/8-inch diameter pistons, 2-inch stroke, and a displacement of 56½ cubic inches per minute. The other system has a commercial, three-plunger pump with a displacement of 250 cubic inches per minute and a rated delivery of 200 cubic inches per minute at 22,500 pounds per square inch. The commercial type is available in the two-plunger or three-plunger style.

A pump with less delivery capacity would probably be more satisfactory for this last-mentioned installation, so as to have a smaller ratio of pump-delivery capacity to cylinder volume. In many of the commercial pumps the valve gland with its gasket is similar to the design shown in Figure 2. This type of gland is troublesome because of leakage at the gasket. In Figure 3 is shown an improved design suggested by this laboratory to prevent leakage. It will be noted in the improved design that the gland does not turn directly on the gasket. There is also shown in this figure the laboratory-designed plug which is used to take the place of a pipe plug. It is believed probable that any of the several pumps on the market can be obtained with these improvements.

In the design or purchase of equipment of this character the fact that water is compressible must be taken into consideration. At a pressure of 1,500 atmospheres (22,500 pounds per square inch) water, according to Amagat, will decrease in volume 4.8 per cent. Clearances that do not ordinarily appear to be excessive in a plunger-type pump for low pressures may become serious at 1,500 atmospheres. If this fact is not fully taken into account in the design, the delivery capacity of the pump may readily be reduced as much as 50 per cent.

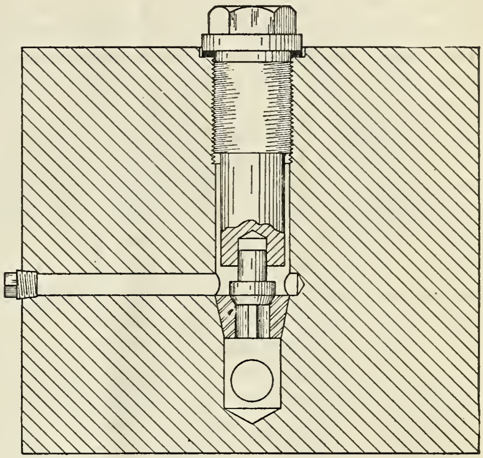


FIG. 2.—Typical pump-valve gland and plug

## TUBING

For pressures up to 1,500 atmospheres (22,500 pounds per square inch) cold-drawn, seamless steel tubing, ¼-inch outside diameter by $\frac{1}{16}$-inch inside diameter, is used for conveying the gas. The tubing used is either of chrome vanadium or chrome molybdenum and has an elastic limit of 60,000 pounds per square inch. All of the tubing used in this system is of the above-mentioned size, except that which connects the hydraulic pump to the blow-off valve and the blow-off valve to the compression cylinder. This tubing is ⅜-inch outside diameter by $\frac{3}{32}$-inch inside diameter, but is of the same composition as the smaller tubing. Tubing of the above sizes is fairly flexible and can be bent to suit various conditions, thus reducing the number of high-pressure joints to a minimum, which is always desirable.

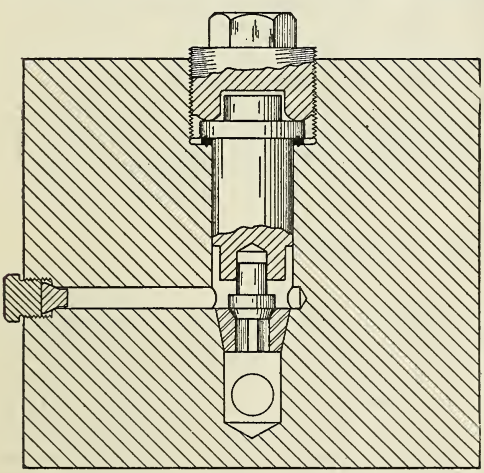


FIG. 3.—Improved pump-valve gland and plug

Copper tubing for low-pressure work has the very desirable quality of pliability and can be readily shaped into many forms that may be desired. Copper tubing of ⅛-inch outside diameter by $\frac{1}{16}$-inch inside diameter and also of $\frac{3}{16}$-inch outside diameter by ⅛-inch inside diameter has met all requirements up to 200 atmospheres pressure (3,000 pounds per square inch).

## CONNECTIONS

Copper tubing is generally attached to the connectors of the various pieces of equipment by a silver-soldered joint. This soldered joint has also been used on steel tubing at pressures up to 1,000 atmospheres (15,000 pounds per square inch). The great objection to silver-soldered joints is that the personal factor enters too largely into their fabrication. More satisfactory methods of joining are now available, and the use of silver-soldered joints is strongly disapproved, especially for high pressures. Detailed dimensions of the various parts required with this connection for ¼-inch outside diameter by $\frac{1}{16}$-inch inside diameter tubing and for ⅜-inch outside diameter by $\frac{3}{32}$-inch inside diameter tubing are shown in Figure 4. The tubing is cut with a truncated cone tip having a 59° angle. A left-hand thread is cut on the tubing, on which a threaded steel collar is fitted. A connector gland slipped over the tubing bears against the collar and forces the cone tip of the tubing against the 60° cone seat cut in the body of the apparatus. This gives the required line contact joint, a desirable feature for gas sealing at high pressure. No great amount of force is necessary to make a tight joint with connections such as these, a 6-inch wrench being sufficient.

Figure 4 also shows details of a cross connection and of a tee connection. Both of these connections are made for the ¼-inch outside diameter by $\frac{1}{16}$-inch inside diameter tubing.

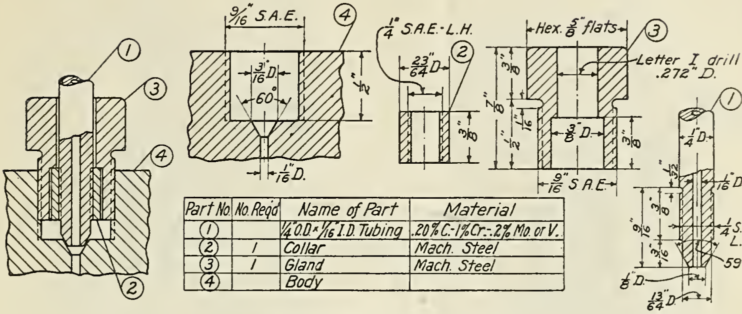
## VALVES

A straightway valve and a cross valve made for the ¼-inch outside diameter by $\frac{1}{16}$-inch inside diameter tubing are shown in Figure 5. Although these valves are built for a pressure of 1,500 atmospheres (22,500 pounds per square inch), the noticeable feature is their size. The largest one, the cross valve, has a body only 2½ inches by 2 inches by 1 inch over-all dimensions. The valve tip is hardened and ground to a 60° angle and fits into the seat, which is not hardened. The soft metal seat permits regrinding when necessary. Care should be taken that only the valve tip, as shown by the drawing, is hardened, as some difficulty may be experienced if too much of the stem is hardened.

## PRESSURE CYLINDERS

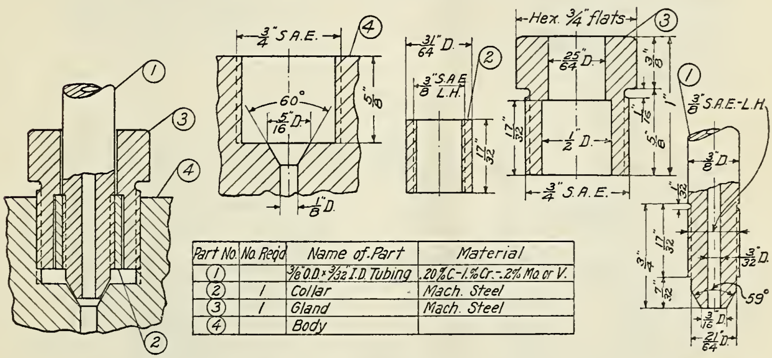
Cylinders with two different types of head are used on the two compression systems. The disk-closure type is shown in Figure 6. The compression and storage cylinders are exactly alike. The cylinder shown is 10½ inches outside diameter by 3 inches inside diameter by 21 inches long and has a total volume of 148 cubic inches. The closure is effected by means of a disk bearing on a copper gasket and secured by studs. The cylinders used at this laboratory were made of gun forgings of the following composition: 3.23 per cent nickel, 0.25 per cent carbon, 0.38 per cent manganese, 0.19 per cent copper, and 0.16 per cent silicon. They have an elastic limit of 63,000 pounds per square inch and an ultimate tensile strength of 92,000 pounds per square inch. The heads, which are made of the same material as the cylinders, are 4⅞ inches thick and are secured by ten 1¼-inch diameter stud bolts. These studs are made of 3½

1/4" × 1/16" TUBING CONNECTION



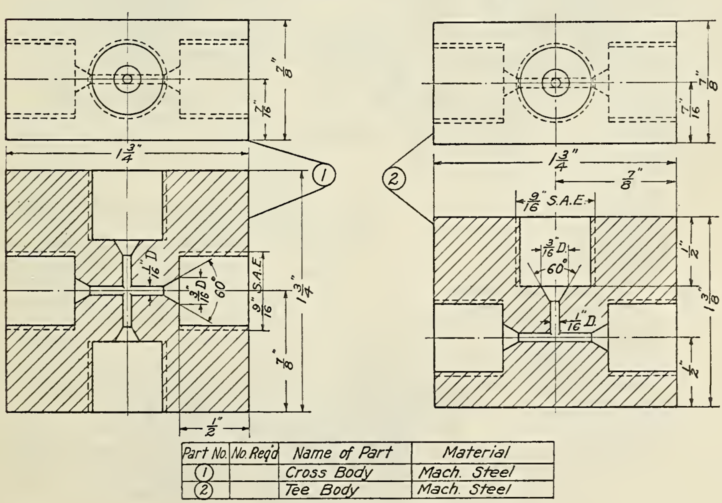

| Part No. | No. Req'd | Name of Part | Material |
|---|---|---|---|
| 1 | | 1/4" O.D. × 1/16" I.D. Tubing | .20% C.-1% Cr.-.2% Mo. or V. |
| 2 | 1 | Collar | Mach. Steel |
| 3 | 1 | Gland | Mach. Steel |
| 4 | | Body | |

3/8" × 3/32" TUBING CONNECTION



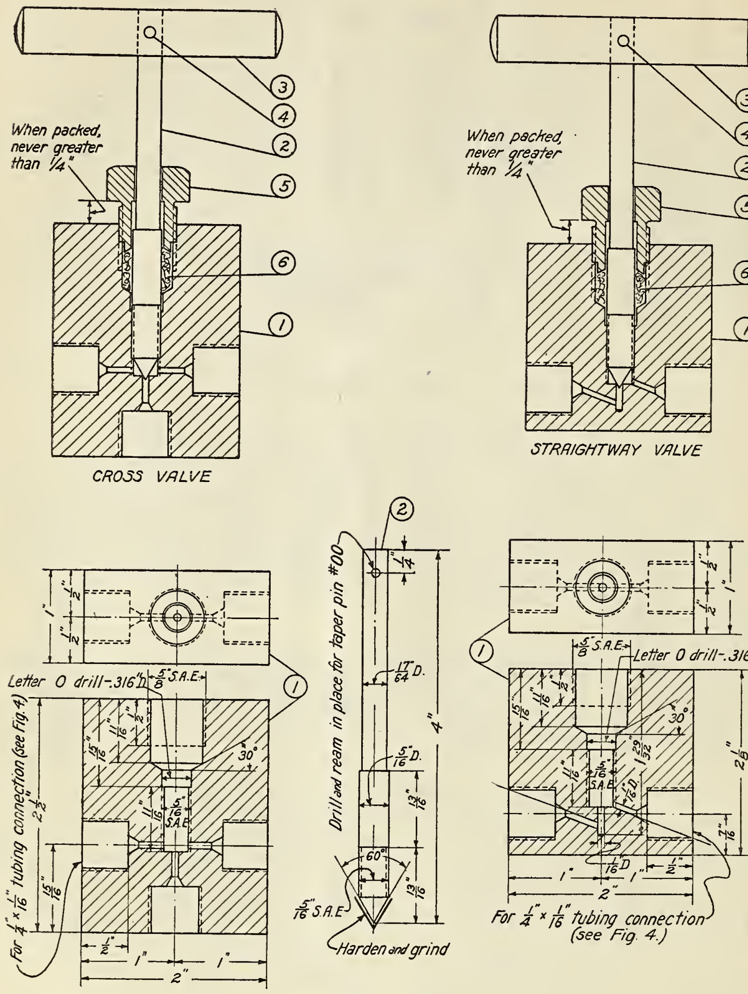

| Part No. | No. Req'd | Name of Part | Material |
|---|---|---|---|
| 1 | | 3/8" O.D. × 3/32" I.D. Tubing | .20% C.-1% Cr.-.2% Mo. or V. |
| 2 | 1 | Collar | Mach. Steel |
| 3 | 1 | Gland | Mach. Steel |
| 4 | | Body | |

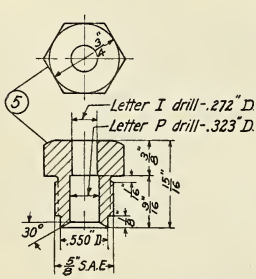
CROSS AND TEE CONNECTIONS FOR 1/4" × 1/16" TUBING

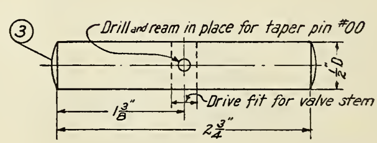



| Part No. | No. Req'd | Name of Part | Material |
|---|---|---|---|
| 1 | | Cross Body | Mach. Steel |
| 2 | | Tee Body | Mach. Steel |

FIG. 4.—Connections for tubing

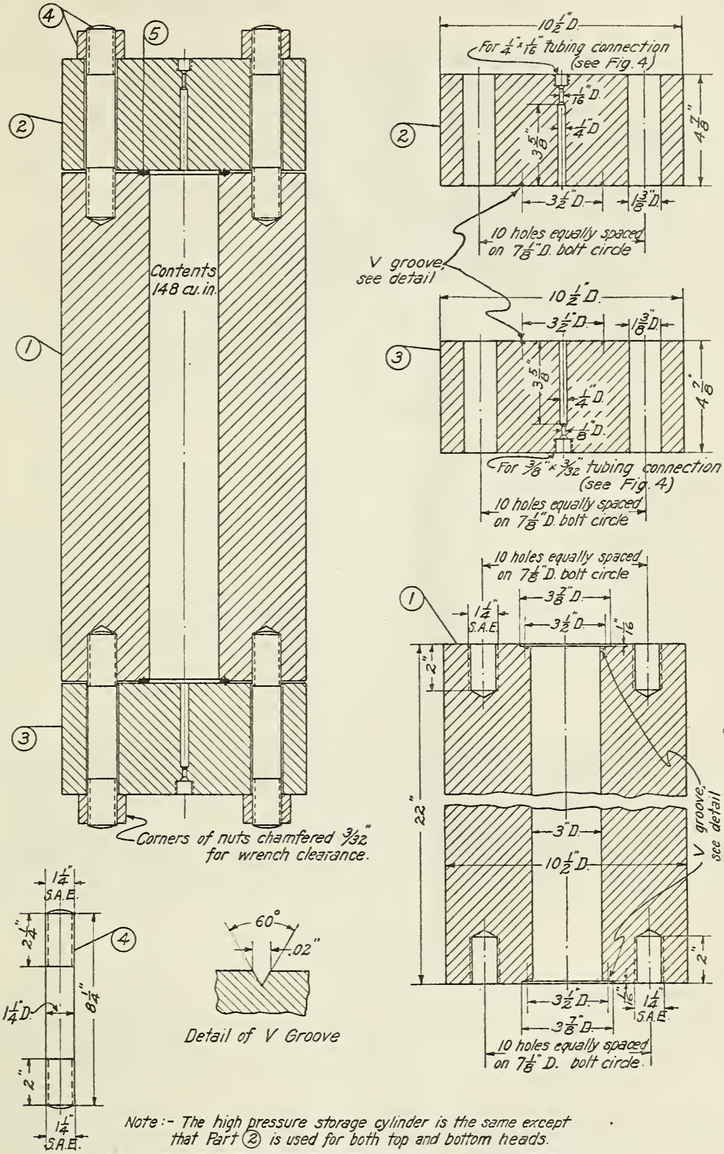



| Part No. | No. Req'd | Name of Part | Material | Remarks |
|---|---|---|---|---|
| 1 | 1 | Valve Body | Mach. Steel | |
| 2 | 1 | Valve Stem | Drill Rod | |
| 3 | 1 | Handle | Mach. Steel | |
| 4 | 1 | Taper Pin | Steel | Std No. 00-½" long |
| 5 | 1 | Packing Gland | Mach. Steel | |
| 6 | | Packing | Shredded Metallic (Lead) | |

FIG. 5.—Valves




| Part No. | No. Reqd. | Name of Part | Material | Remarks |
|---|---|---|---|---|
| 1 | 1 | Cylinder | Nickel Steel or Cr. V. Steel | |
| 2 | 1 | Top Head | Nickel Steel or Cr. V. Steel | |
| 3 | 1 | Bottom Head | Nickel Steel or Cr. V. Steel | |
| 4 | 20 | Stud Bolt & Nut | Nickel Steel | |
| 5 | 2 | Gasket | Annealed Copper | 3 7/8" O.D. x 3" I.D. x 3/16" thick |

FIG. 6.—Compression cylinder, disk-closure type

20398—29——2

per cent nickel steel, having an elastic limit of 70,000 pounds per square inch. The annealed copper gasket is of the flat type. It is unconfined and is centered by means of a slight recess cut in the cylinder.

The ring-closure type is shown in Figure 7. The cylinder shown is 12 inches outside diameter by 4 inches inside diameter by 36 inches long and has a total volume of 275 cubic inches. The head bears on the gasket, and by means of special bolts passing through the retaining ring pressure for making a gas-tight joint is applied as near as possible over the mean circumference of the gasket. The shells are made of gun forgings, similar to the other type. The heads and retaining rings are a good-grade steel forging containing 1 per cent chromium, 0.2 per cent vanadium, and 0.3 per cent carbon. The bolts are 3½ per cent nickel steel with an elastic limit of 70,000 pounds per square inch. A small 60° V groove is cut in the cylinder and in the head in such a position that the copper gasket will flow into these grooves when the gasket is compressed. Such a V groove is used wherever a copper gasket is employed to make a gas-tight joint.

The above cylinders were gun forgings which were bored the entire length when obtained, making necessary a closure for both ends. When purchasing new cylinders, a saving can be effected by having the cylinders bored the proper depth from one end, thus requiring only one head to be made. If this is done, care must be taken that the solid end is perfect, as leakage may occur due to "piping" or other defects in the forging. The joints of these cylinders were made tight by the use of a socket wrench with a 6-foot handle.

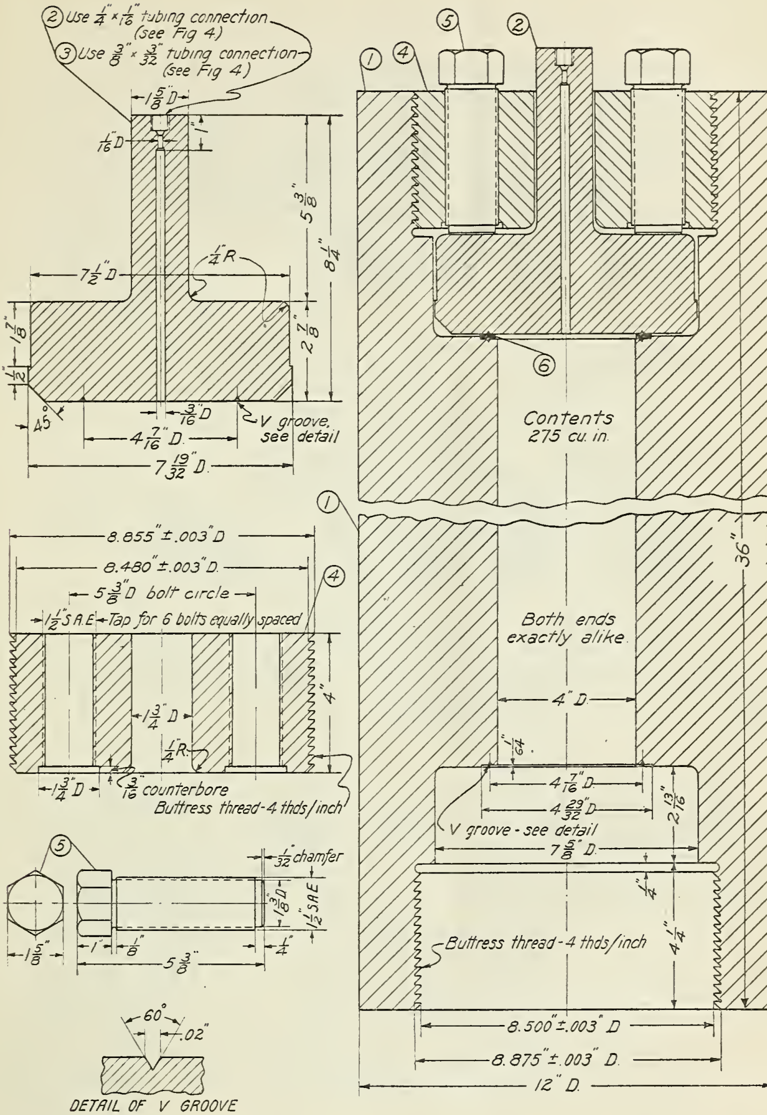
## BLOW-OFF VALVE

A blow-off valve is required for draining the water from the compression cylinder at intervals during the compression operation. This valve is shown in Figure 8, which is self-explanatory. The valve acts as a combination drain valve, a connection for the discharge side of the hydraulic pump, and a connection to the dial gauge, which is water sealed.

## DEAD-WEIGHT GAUGE

For obtaining approximately correct pressure readings, a Bourdon tube gauge is used. Experience with a number of Bourdon tube gauges has shown them to be unsatisfactory for this class of work. To date, those gauges which have given the least amount of trouble have been of French manufacture. This type of gauge withstands operating conditions much better when a hydraulic reservoir is inserted in the line, thus subjecting the Bourdon tube to hydraulic pressure instead of to the gas pressure direct.

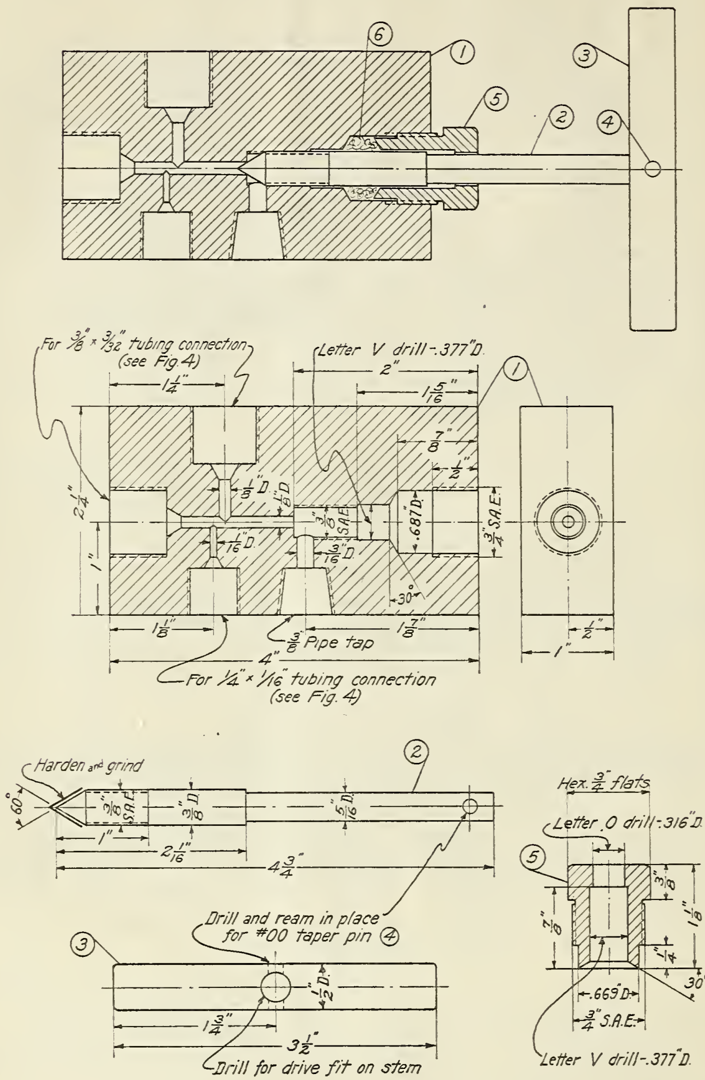
Scientific data require a knowledge of the correct pressure. The most satisfactory accurate gauge for high pressure is the "dead-weight" or floating-piston type. The gauge designed and built at this laboratory is shown in Figure 9. The authors had hoped that it would be possible to show complete details of this gauge, but owing to the multiplicity of parts, not only of the gauge itself but of the




Note :- The high pressure storage cylinder is the same except that Part (2) is used for both top and bottom heads.

| Part No. | No. Req'd | Name of Part | Material | Remarks |
|---|---|---|---|---|
| (1) | 1 | Cylinder | Ni. Steel or Cr. V. Steel | |
| (2) | 1 | Top Head | Cr. V. Steel | |
| (3) | 1 | Bottom Head | Cr. V. Steel | |
| (4) | 2 | Retaining Ring | Cr. V. Steel | |
| (5) | 12 | Special Bolts | Ni. Steel | |
| (6) | 2 | Gasket | Annealed Copper | 4 29/32" O.D. - 4" I.D. - 1/8" thick |

FIG. 7.—Compression cylinder, ring-closure type




| Part No. | No. Reqd. | Name of Part | Material | Remarks |
|---|---|---|---|---|
| 1 | 1 | Body | Mach. Steel | |
| 2 | 1 | Valve Stem | Drill Rod | |
| 3 | 1 | Handle | Mach. Steel | |
| 4 | 1 | Taper Pin | Steel | Std. No. 00-1/2" long |
| 5 | 1 | Packing Gland | Mach. Steel | |
| 6 | | Packing | Shredded Metallic (Lead) | |

FIG. 8.—Blow-off valve

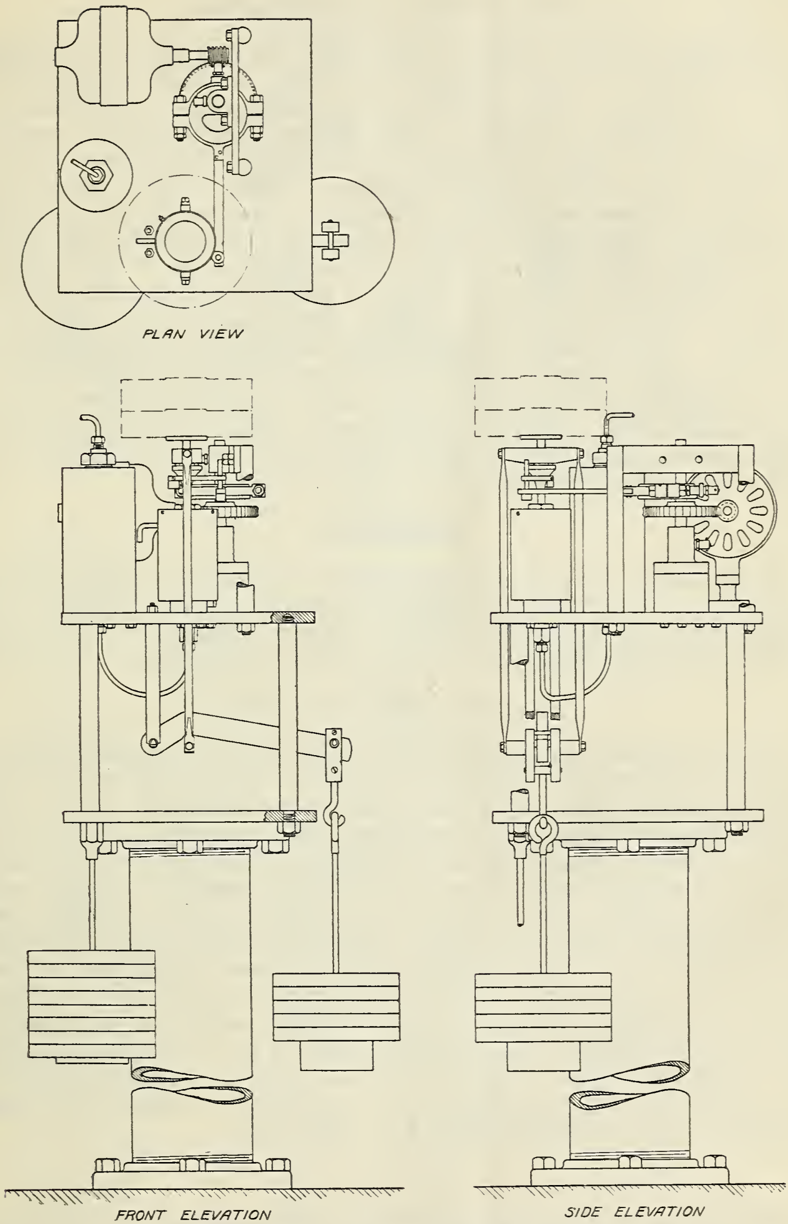



FIG. 9.—1,500-atmosphere dead-weight gauge

oil reservoir, oil heater, and oscillating mechanism, they feel such detailed information is beyond the scope of this circular.

## MANUAL-PRESSURE REGULATOR

To obtain an exact pressure at the time of compression, or to offset a slight drain on the system during a test, a manual-pressure regulator is employed. The details and assembly of this regulator are shown in Figures 10 and 11, respectively. The regulator consists essentially of a Monel metal piston fitting into a chrome-vanadium cylinder. The piston operates against a water column maintained by a hydraulic reservoir and is activated by means of a screw to which is fastened a handwheel or arm. Monel metal is used for the piston to overcome any difficulties due to corrosion. One of the features of this regulator is the arrangement for packing. The packing proper consists of annular rings of babbitt (50 per cent lead and 50 per cent tin). These babbitt packing rings are placed in the stuffing box alternately with annular steel rings. Both the steel and babbitt rings are so cut that when pressure is applied to them the desired seal is made at the piston and the cylinder wall. This style of packing has been used similarly for gas pressure and also has proved effective in this case as a seal for hydraulic pressure.

## RESERVOIR

In the line to the dead-weight gauge an oil reservoir is placed, and preceding both the manual-pressure regulator and the Bourdon tube gauge there is a hydraulic reservoir. All of these reservoirs are of the same construction, the details of which are shown in Figure 12.

## MATERIAL SPECIFICATIONS

On the detailed drawings of the various pieces of equipment, various kinds of material have been specified, and in order to avoid lengthy explanations only brief specifications have been given. The different materials are to be considered of the quality here specified. Machine steel is considered as a straight 0.2 per cent carbon steel, having an elastic limit not less than 35,000 pounds per square inch. Chrome-vanadium steel contains 1 per cent chromium, 0.2 per cent vanadium, and 0.3 per cent carbon, and has an elastic limit of 85,000 pounds per square inch. Nickel steel is a steel containing 0.3 per cent carbon and 3.5 per cent nickel, having an elastic limit of 70,000 pounds per square inch. The steel tubing used is a cold-drawn, seamless steel tubing with the composition 1 per cent chromium, 0.2 per cent molybdenum, and 0.3 per cent carbon, or 1 per cent chromium, 0.2 per cent vanadium, and 0.3 per cent carbon, and having an elastic limit of 60,000 pounds per square inch.

## COSTS

For anyone who may be considering the possibility of installing a compression system such as has been described, the cost of the apparatus will be of interest. Approximate costs of the equipment are listed below. These costs are simply estimates and are not to be taken in any sense as actual prices.

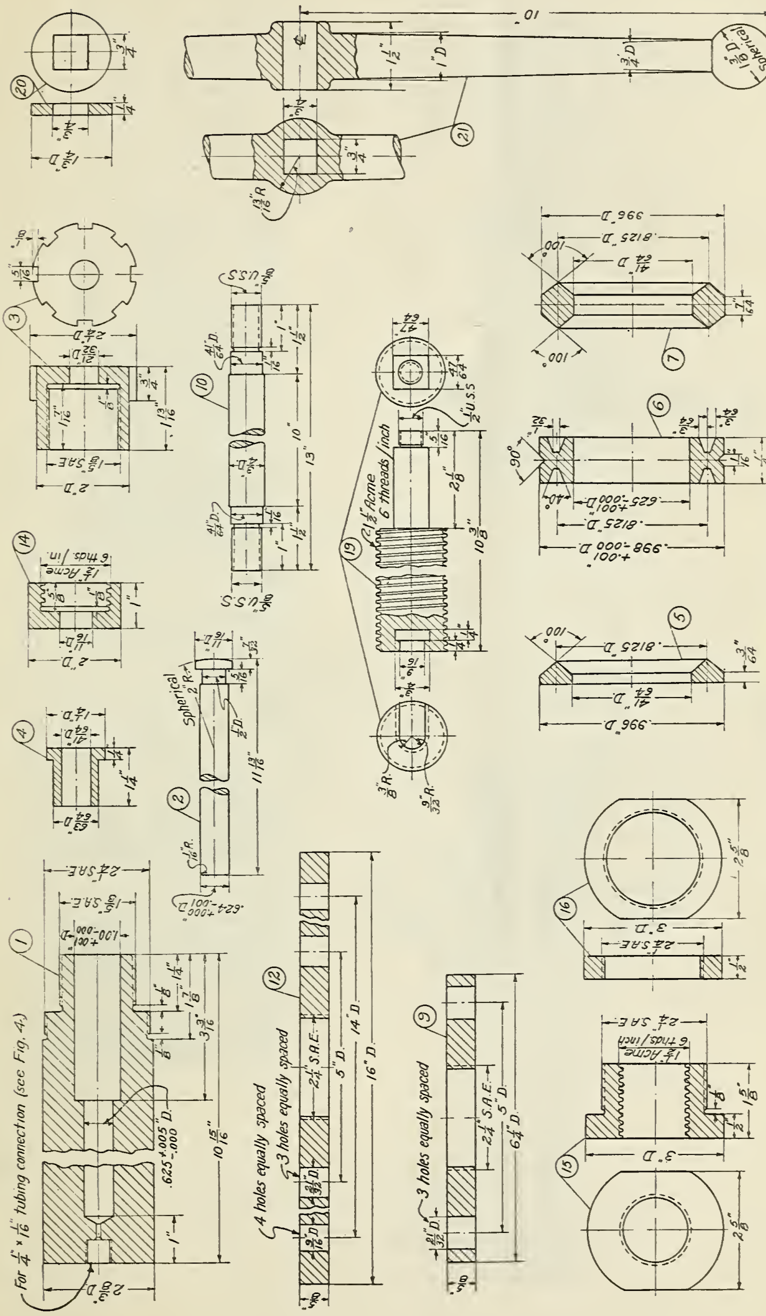
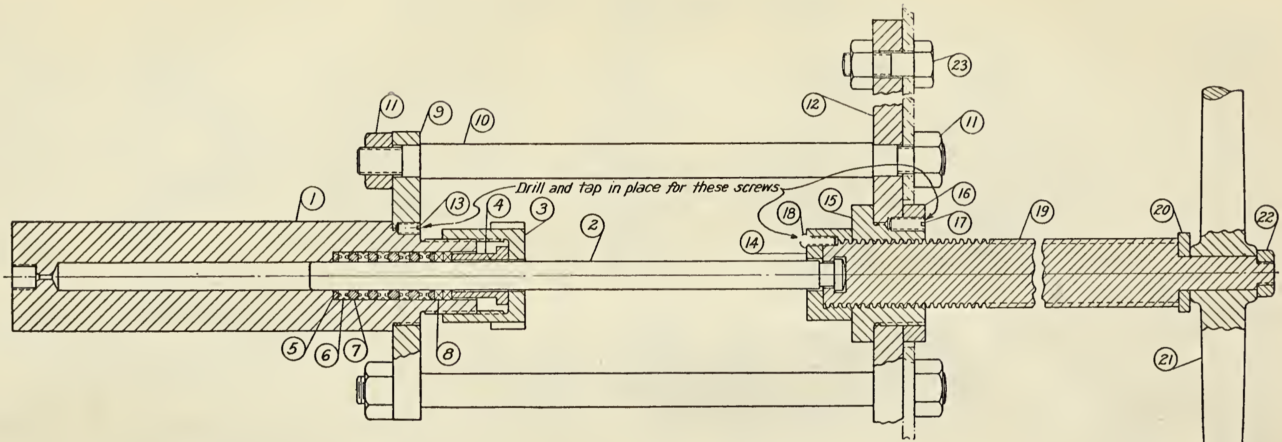
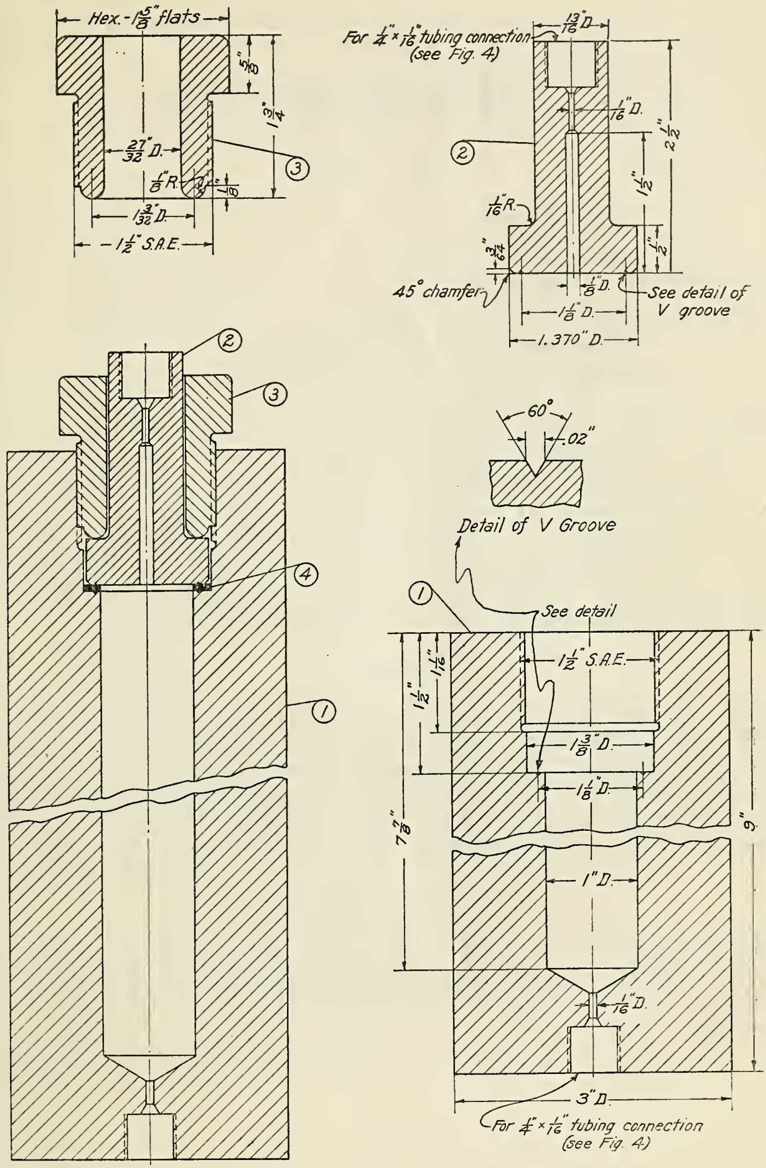



Fig. 10.—Details of manual-pressure regulator




| Part No. | No. Req'd | Name of Part | Material | Remarks | Part No. | No. Req'd | Name of Part | Material | Remarks |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | Cylinder | Cr. V. Steel | | 13 | 1 | H'dless Set Screw | | 1/4" diam. × 1/2" long |
| 2 | 1 | Plunger | Monel Metal | | 14 | 1 | Forward Stop | Mach. Steel | |
| 3 | 1 | Packing Nut | Mach. Steel | | 15 | 1 | Stem Bushing | Mach. Steel | |
| 4 | 1 | Packing Gland | Mach. Steel | | 16 | 1 | Bushing Collar | Mach. Steel | |
| 5 | 2 | End Spacer | Mach. Steel | | 17 | 1 | H'dless Set Screw | | 5/16" diam. × 3/4" long |
| 6 | 5 | Packing Ring | Babbitt | 50% Lead & 50% Tin | 18 | 1 | Cap Screw - R. H. | | 3/16" diam. × 5/8" long |
| 7 | 4 | Spacer Ring | Mach. Steel | | 19 | 1 | Plunger Screw Stem | Mach. Steel | |
| 8 | 2 | Packing Ring | Flax | 3/16" × 1/4" | 20 | 1 | Back Stop | Mach. Steel | |
| 9 | 1 | Rear Plate | Steel | | 21 | 1 | Two Arm Handle | Mach. Steel | |
| 10 | 3 | Tie Rod | C. R. Steel | | 22 | 1 | Check Nut | | 1/2" U. S. St'd |
| 11 | 6 | Nut | | 5/8" U. S. St'd | 23 | 4 | 1/2" St'd Bolt & Nut | | 1 1/2" long |
| 12 | 1 | Front Plate | Steel | | | | | | |

FIG. 11.—Assembly of manual-pressure regulator




| Part No. | No. Reqd | Name of Part | Material | Remarks |
|---|---|---|---|---|
| 1 | 1 | Body | Cr. V. Steel | |
| 2 | 1 | Head | Cr. V. Steel | |
| 3 | 1 | Retainer | Cr. V. Steel | |
| 4 | 1 | Gasket | Copper (Annealed) | 1 3/8" O.D. × 1" I.D. × 1/16" thick |

FIG. 12.—Reservoir for oil or water

ESTIMATE OF COST OF HIGH-PRESSURE EQUIPMENT

| | |
|---|---|
| Compressor, 4,000 pounds per square inch, 5 cubic feet (without motor) | $750.00 |
| Low-pressure storage cylinder (1½ cubic feet volume) | 50.00 |
| Hydraulic pump (without motor) | 650.00 |
| ¼-inch outside diameter by $\frac{1}{16}$-inch inside diameter tubing, per foot | .21 |
| ⅜-inch outside diameter by $\frac{3}{32}$-inch inside diameter tubing, per foot | .58 |
| Tee connector | 5.00 |
| Cross connector | 6.00 |
| Straightway valve | 12.00 |
| Cross valve | 12.00 |
| High-pressure cylinders, each | 400.00 |
| Blow-off valve | 30.00 |
| Dead-weight gauge | 700.00 |
| Manual pressure regulator | 275.00 |
| Reservoir | 15.00 |
| Bourdon tube gauge | 50.00 |
| Gland, collar, and finishing ends of tubing, each | 2.00 |

To the uninitiated, experimental work at these pressures may seem dangerous, but the danger is not so great as the pressure would indicate. Most of the work is done with small volumes. During six years of experimenting with high-pressure apparatus in this laboratory, no one has been injured in any way. Safety precautions, however, are taken to insure against personal injury. The high-pressure equipment, with the exception of the hydraulic pump and the dead-weight gauge, is placed behind a ¼-inch armor-plate barricade. The control valves and regulator are mounted on this armor plate and can be operated from outside the barricade.

## SUMMARY

This circular describes the operation of a system for experimental work with gases at normal temperature and at pressures up to 1,500 atmospheres (22,500 pounds per square inch). Detailed drawings of each piece of equipment are shown, permitting the complete construction of the system described. Descriptions of the apparatus, together with approximate costs of its various parts, are included.

## ACKNOWLEDGMENT

Acknowledgment is made to Mr. J. F. Mullins, chief engineering aid, for his help in the design and construction of this apparatus, and to Mrs. C. Sherry, assistant draftsman, for the preparation of the drawings.

## ORGANIZATION OF THE UNITED STATES DEPARTMENT OF AGRICULTURE

January 5, 1929

| | |
|---|---|
| *Secretary of Agriculture* | W. M. JARDINE. |
| *Assistant Secretary* | R. W. DUNLAP. |
| *Director of Scientific Work* | A. F. WOODS. |
| *Director of Regulatory Work* | WALTER G. CAMPBELL. |
| *Director of Extension* | C. W. WARBURTON. |
| *Director of Personnel and Business Administration.* | W. W. STOCKBERGER. |
| *Director of Information* | M. S. EISENHOWER. |
| *Solicitor* | R. W. WILLIAMS. |
| *Weather Bureau* | CHARLES F. MARVIN, *Chief.* |
| *Bureau of Animal Industry* | JOHN R. MOHLER, *Chief.* |
| *Bureau of Dairy Industry* | O. E. REED, *Chief.* |
| *Bureau of Plant Industry* | WILLIAM A. TAYLOR, *Chief.* |
| *Forest Service* | R. Y. STUART, *Chief.* |
| *Bureau of Chemistry and Soils* | H. G. KNIGHT, *Chief.* |
| *Bureau of Entomology* | C. L. MARLATT, *Chief.* |
| *Bureau of Biological Survey* | PAUL G. REDINGTON, *Chief.* |
| *Bureau of Public Roads* | THOMAS H. MACDONALD, *Chief.* |
| *Bureau of Agricultural Economics* | NILS A. OLSEN, *Chief.* |
| *Bureau of Home Economics* | LOUISE STANLEY, *Chief.* |
| *Plant Quarantine and Control Administration* | C. L. MARLATT, *Chief.* |
| *Grain Futures Administration* | J. W. T. DUVEL, *Chief.* |
| *Food, Drug, and Insecticide Administration* | WALTER G. CAMPBELL, *Director of Regulatory Work, in Charge.* |
| *Office of Experiment Stations* | E. W. ALLEN, *Chief.* |
| *Office of Cooperative Extension Work* | C. B. SMITH, *Chief.* |
| *Library* | CLARIBEL R. BARNETT, *Librarian.* |

This circular is a contribution from

| | |
|---|---|
| *Bureau of Chemistry and Soils* | H. G. KNIGHT, *Chief.* |
| *Fertilizer and Fixed Nitrogen Investigations.* | F. G. COTTRELL, *Chief.* |



ADDITIONAL COPIES
OF THIS PUBLICATION MAY BE PROCURED FROM
THE SUPERINTENDENT OF DOCUMENTS
U. S. GOVERNMENT PRINTING OFFICE
WASHINGTON, D. C.
AT
10 CENTS PER COPY

▽